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Potential Power Savings of Approximately 3000 kVA in the Operation of the Fermi Cyclotron

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Introduction

The Fermi Cyclotron at the Fermi Laboratory operates at a field of 15.8 kG requiring 2,030,000 ampere turns. The present exciting coils are powered by four Transrex 500 B power supplies delivering 5000 amps at 400 volts dc. Total system demand considering line loss, power factor, etc. is approximately 3000 kVA at the substation. This is the second largest load on the Neutrino beam line and taxes the system capacity when all beam elements are energized.

It should be noted that the coils are nearly 20 years of age and were insulated as per commercial practice of 20 years ago. They are presently operated at more than twice the power that they were at the University of Chicago. Prior to re-insulation at Fermilab the coils were inspected, cleaned and re-furbished. However, commercial motor-generator experience would indicate the likelihood of failure at some future date.

When, and if, a failure occurs, five courses of action are possible:

(1) turn it off. (This is highly unlikely in a

productive facility and alternatives will be sought.

(2) jumper out the failed pancake and its mirrored counterpart and continue to run at lower field for as long as possible.

(3) perform (2) and wind conventional coils to be installed at a determined future date.

(4) perform (2) and wind superconducting coils as per the 15' cryogenic bubble chamber to be installed at a future predetermined date.

(5) perform (2) and then modify the existing coils to operate in the superconducting mode.

Alternatives (4) and (5) seem to be the most attractive. Alternatitve (3) would probably be just as expensive as (4) and (5) and one would still be saddled with the power problem.

Alternative (5) is examined here for feasibility and cost. The cost of alternative (4) can be extrapolated from data for the 15-foot bubble chamber.

It should be noted that any decision considering scrap value of the existing coils should be precluded since the coils are contaminated and have no scrap value.

Approach

The approach desired herein is to modify the existing coils to operate in the superconducting mode. Simply stated, this would be done by soldering superconducting wire (cable) into the existing copper coils and utilizing the existing coils as the liquid helium vessel and support structure for the superconductor.

Utilizing more strands in the NbTi cable produced by Supercon for the Fermilab Energy Doubler program will produce a cable that will operate in a field of 2 Tesla with the margin of safety desired. It is imperative that the NbTi cable be operated at approximately 4.2° to 4.7° K. This can be achieved by firmly soldering the superconductor into the existing copper coils and cooling the entire coil down to liquid helium temperature (4.2° K).

The existing coils are wound from 2" square OFHC copper with a 1 1/8" diameter centered cooland hold. The fact that the coils now operate at 5000 amps indicates structural integrity. The successful operation of the Fermilab Energy Doubler test loop has proven that liquid helium can be pumped over more than 400 feet with negligible heat gain and pressure differentials measured in inches of water (1 psi = 28.08 inches of water). These data are currently being reduced and will produce the first real numbers in this field.

It should be noted that in no case are we seeking to advance the state of the art. Salvage of the existing coils is straightforward. Affixing the superconductor with consistent continuity over the lengths that we are talking of requires some engineering and care but is not unreasonable. Refrigerators (liquefiers) adequate for the job are available commercially. A little clever cryostat design can minimize the heat leak associated with mechanical support of the coil packages. The major refrigeration load can be taken using LN_2. This markedly reduces the machinery requirements.

Recent developments in flux pump design by Awschalom, Droege, Kerns, Purcell et. al in Research Services make such a high current modification all the more attractive since one is not now faced with the demands imposed by high current leads. It might indeed be appealing to consider even higher currents if higher fields can be obtained and are desirable. Once one is operating in the superconducting mode, higher currents are essentially free. The fabrication proposed should yield a structure that is more monolithic than that at present.

Procedure

Modification of the magnet falls into distinct steps:

(1) dis-assembly of the coils from the magnet.

(2) salvage of the coil copper with care taken to preserve the proven integrity of the present brazed joints and prevent the spread of contamination.

(3) removal of two inner turns from each pancake to make room for the cryostat.

(4) grooving of the copper to receive the superconductor.

(5) attachment of the superconductor to the copper.

(6) "re-insulation" using conventional techniques with G-10 sheets for layer insulation and strips for turn insulation with tape for ground and structural properties.

(7) vacuum impregnation of each of the fourteen pancakes to assure a sound monolithic structure to preclude wire shift (even though "training" is acceptable since this is a dc magnet).

(8) assembly of the upper and lower coil pancakes of seven pancakes each and the making of the interconnections.

(9) assembly of the coil pancakes into two distinct cryostats. This allows sequential testing of coils, LN_2 shields, vacuum vessel, etc.

(10) installation of the cryostats into the magnets.

(11) installation of interconnections between cryostats, piping, instrumentation, flux pump and leads, and cryogenic connections. (It should be noted that there is more than adequate room for the above due to the conservative design of the original yoke.)

(12) installation of the cooldown system, operating system (liquefier), helium recovery system, LN_2 supply and associated piping, controls and power supply.

(13) cooldown to LN_2 temperature.

(14) cooldown to 4.2° K.

(15) power.

(16) verify field map.

Dis-assembly

Dis-assembly would follow exactly in reverse the procedure Belding Engineering used in the installation at NAL.[1]

Copper Salvage

The insulation is of varnished cambric with a glass overlay and must be removed by "burning", i.e. heating to about 700°F in an insulated box. The heating can be done electrically. The charred residue would be removed by conventional sand blasting with all contaminated material constrained. Residue in the fluid passage would be analyzed and then properly removed to preclude contamination of the helium loop.

Coil Preparation

The coil would then be helium leak checked after LN_2 "shocking".

A carbide tipped rooter would cut a groove into the copper to receive the NbTi cable as shown.

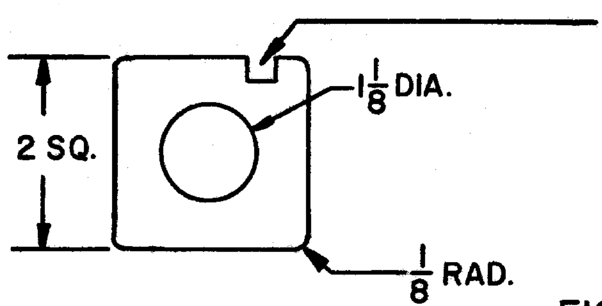


FIG. 1

The edge of the copper serves as the router guide and double slot widths are cut for splices.

Superconductor Attachment

It is imperative that the NbTi "cable" be firmly soft soldered into the groove to provide continuous thermal bond and that no weak links exist in the thermal path. It is desirable to apply the solder when the copper is locally above the melting point of the solder. There are several Indium alloys that flow in the region of 200° F and exhibit good bond characteristics. The entire coil structure would be heated to about 30° F below the flow point of the solder, the solder preplaced in the groove and pre-tinned superconductor rolled into the groove as the copper is locally heated to the flow point by induction heating or carbon blocks. This must be followed by a heat "thief" or chill block to make sure that the superconductor stays in place. It may also prove feasible to "stake" the superconductor into the groove and then add solder and flux as the localized heating progresses. Superconductor would be brought right out to the lead ends so that continuity of superconductor could be maintained thru the subsequent jumper attachments.

Re-insulation

G-10 sheets for layer insulation and G-10 strips for turns insulation would maintain the same gaps as the original winding. The entire pancake would then be taped as per conventional practice. It is probably most feasible to vacuum impregnate each pancake. The mold need not be extremely precise but should press the structure firmly. Extreme flatness is not a pre-requisite and sealing of the molding form should pose no problems that have not already been solved by Hanson et. al in the Magnet Facility. An epoxy system has not been chosen but it is imperative that the temperature rise during the cure cycle be held well below the melting point of the bonding solder. This is an area that requires further study since one would desire structural integrity at 4.2° K. However, this is a problem that will be faced and hopefully solved well before this project is ever attempted.

Assembly of Pancakes into Packages

The stacking would be the exact reverse of removal. The coil to coil jumper size would be increased in mass to assure that this area never approaches T_c. It has proven advantageous to double-up on the superconductor on jumpers in this technique. Likewise each coil end should be instrumented so that it can be verified that each coil pancake is superconducting prior to powering and for subsequent analysis.

Assembly into Cryostats

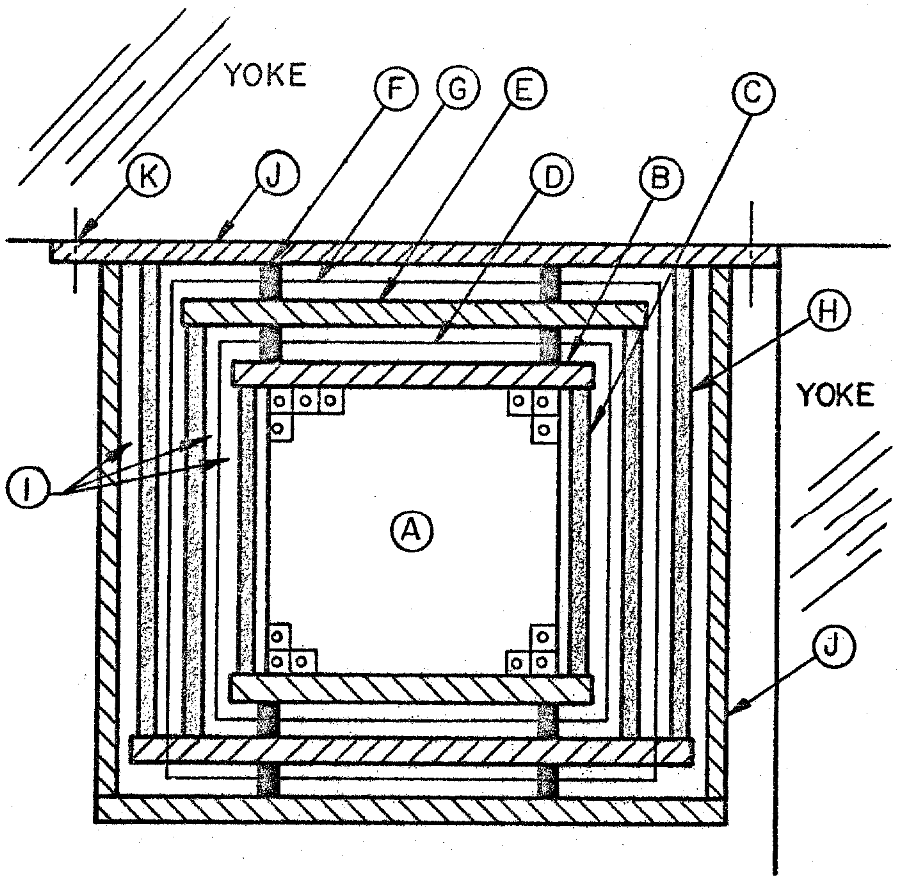
The packages would be assembled onto support plates as per the original assembly. This in turn would be placed into the LN_2 shield such that the major heat leak thru the bearing blocks for the support plates is from the helium vessel (coils) to the LN_2 shield (4.2° K to 78° K) as per Fig. 2 below. The load is then transmitted from the appropriate points on the LN_2 shield to the vacuum box via long bolts and columns as per standard helium dewar design.

Installation of Cryostats into Magnet

The vacuum box would be bolted into the magnet yoke in a way similar to the present arrangement. This allows pretesting of everything up to this point.

Installation of Interconnections

In the top cryostat there will be two header boxes; one for in-flowing LHe and one for the return LHe. Tubes from the coolant passages of each of the pancakes would connect to the appropriate header box with electrical isolation via a ceramic insulator. It should be noted that the lower



A. Coil package

B. Pressing or clamping plates

C. Tie rods (stainless steel)

D. Superinsulation

E. LN_2 shield reinforced at areas of tie bolts and support blocks.

F. G-10 support tubes at reinforced spots on LN_2 shield. Coil package takes part of vacuum load and tubes act as bearing blocks to yoke. Staggered for long heat leak.

G. Superinsulation

H. Support rods

I. Vacuum

J. Vacuum can

K. Bolts to yoke

Figure 2

and upper cryostats are displaced vertically in the magnet yoke by about 10 feet midplane to midplane. The total pancake coolant length is approximately 475 feet. As stated before, the experience in the Fermilab test loop indicates that our ΔP required to provide sufficient LHe flow thru the passage to offset the radiant and support heat leak will be in the order of fractions of a psi. 16.7 feet of liquid helium equal 1 psi. Therefore the upper coil bundles will require orifices to assure equalized flow and the upper and lower pancakes that have supports to the LN_2 shield will require larger orifices to compensate for their higher conductive heat load. Orifice sizing must await definite reduction of the data taken in the test loop program.

The lower cryostat would also contain similar header boxes. These would be connected via a transfer line inside a LN_2 shield. Doubled up superconductor must pass thru these transfer lines to provide electrical interconnection between the lower and upper coil packages and from one electrical extremity of the lower package to the flux pump. These jumpers must be mechanically restrained, insulated from ground, and yet not inhibit free LHe flow.

Installation of the Cryogenics

It is assumed that the coil packages (LHe vessel), LN_2 shield, and interconnections will be properly insulated. A final leak check from the header boxes would be performed prior to the final sealing of the vacuum box. At that time there would be seven major connections to the outside world; LHe in and out, LN_2 in and out, vapor cooled leads to the flux pump, and vacuum. Instrumentation feed through is relatively straight forward.

Two very distinct refrigeration problems exist; cool-down and steady state operation. We would prepare cooldown to LN_2 temperature (78° K) with one system and then the hook-up of the steady state system to carry the cooldown to 4.2° K.

Cooldown to 78° K

Cooldown of the LN_2 shield simply requires hookup to an LN_2 tanker and monitoring of the effluent gas until stability at 78° K is achieved. It is then assumed that proper controls would maintain this effluent temperature during the cooldown of the LHe vessel (coils).

Since we have approximately 26,000 pounds in the helium vessel, we would require between 3640 and 5720 liters of LN_2 to cool down to 78° K [2] depending on efficiency and the rapidity of cooldown desired. The helium recovery system may be used for circulation of the gas during this phase.

Cooldown to 4.2° K

At this point one has to decide whether to size the liquefier (refrigerator) assembly for cooldown or steady state operation and to determine the rapidity desired. Initially it is probably far better to buy the LHe required to get from 78° K to 4.2° K and size the liquefier for steady state. A minimum of 2000 liters [2] of LHe is required for this phase. It would seem obvious at the start to simply buy this LHe.

Cryogenics Consultants, Allentown, Pa. have recently applied for a patent on a scheme whereby LHe is circulated through the other side of a modified CTi 1400 with flow monitored to yield effluent helium gas at 4.2° K.

The LHe vessel (coils) has a surface of about 1400 square feet which would imply a heat load of about 14 watts from the 78° K shield. The LHe pump would supply another 50 watts to the system load and a pessimistic estimate of 50 watts for support heat leaks would appear feasible. Lead loss for the flux pump would be about 3 watts. Thus two CTi 1400's with 3 compressors and LN_2 precooling should suffice.

For initial operation it would seem reasonable to make all change-over from cooldown to steady state operation a manual switchover. Steady state operation would be fully automatic.

Power

Preliminary tests of the flux pump at ANL are encouraging. A test and full scale device should soon be built. A finalized flux pump design must be fixed before the cryostat design can be finalized. Power should be routine with an off-the-shelf power supply.

Verification of Field Map

The Oxford University measurement gear exists and may be utilized to assure that the field map has not changed or, if a noticeable difference is evident, for remapping.

Costs

1)	Rigging	$ 30,000
2)	All coil modification done on site including superconductor (8 man years + materials)	$ 200,000
3)	Refrigeration - 2 CTi 1400's & controls	$ 200,000
4)	Cryostats	$ 200,000
5)	Recovery system	$ 10,000
6)	Cooldown system	$ 10,000
7)	Flux pump and power supply	$ 50,000
8)	Contingency 25%	$ 175,000
	Total	$ 875,000

Time Scale

1. Six months of Engineering, planning, design and procurement prior to shut down from jury-rigged operation.

2. Twelve months shut down to turn on.

Economic Considerations

1)	Operating cost for old device (conventional) 3.0 MW		
	18 GW-Hr @ $10 K/GW-Hr	$180,000	
	LCW Replenishment	25,000	$205,000/yr
2)	Operating cost for new device		
	a) power	$ 18,000	
	b) LN_2 cooldown	1,000	
	c) LN_2 operating	50,000	
	d) LHe cooldown	3,400	
	e) LHe operating	2,000	
	Total		$ 74,400/yr
3)	Operating cost savings (Δ cost/yr)		$130,600/yr

4) Amortization $= \dfrac{\text{modification cost}}{\Delta \text{ cost/yr}}$

$$= \frac{875{,}000}{147{,}000} = \quad \sim 7 \text{ years}$$

5) Power savings @ 6000 Hrs/yr 16 GW-Hrs

References

[1] NAL Internal Report, Cyclotron Magnet Move, W.W. Nestander, Neutrino 72-517 pages 1/6. 5-17-72.

[2] Preliminary Analysis of Refrigeration Requirements for Superconducting Magnets in the Experimental Area of the 200 BeV Accelerator, T.R. Strobridge, D.B. Mann and D.B. Chelton, N.B.S. Report 9259 pages 3/7. 10-31-66.